

COSMOPARTICLE PHYSICS AS A PROBE FOR THE THEORY OF PHYSICAL SPACE-TIME

M.Yu. Khlopov¹ and A.S. Sakharov

Center for Cosmoparticle Physics “Cosmion”, 4 Miusskaya pl., Moscow 125047, Russia

Received 18 July 1995

CosmoParticle Physics studies the foundations of particle physics and cosmology and their fundamental relationship in complex crossdisciplinary links of their indirect effects. This new actively developing field of science has appeared as a natural step in the interaction between particle theory, losing the possibility to probe its theoretical grounds by direct experimental means, and cosmology, finding a physical basis for its fundamental ideas outside the experimentally proven theoretical schemes and having no direct observational evidences on the very early stages of the evolution of the Universe. The lack of direct experimental information on the superhigh energy physics predicted by modern particle theories, and of direct astronomical observations of very early Universe makes CosmoParticle Physics develop an extensive network of indirect physical, astrophysical and cosmological means to study these phenomena in an analysis of a proper combination of their indirect consequences. The modern stage of development of CosmoParticle Physics may provide its useful experience for nontrivial probes of such grounds of the theory of space-time, which cannot be tested by any direct means. On the basis of CosmoParticle Physics it is shown that an extension of the standard electroweak model and QCD, containing a spontaneously broken horizontal local gauge symmetry, provides a quantitatively definite phenomenological description for all basic phenomena of particle physics and cosmology. The model connects the predictions of the standard model with a description of the mass spectrum and mixing of quarks and leptons, predictions of neutrino mass spectrum and parameters of the invisible axion. It provides a quantitative physical basis for the theory of inflation, bariosynthesis and dark matter of the Universe. The complex analysis of physical, cosmological and astrophysical predictions of the model leaves a narrow range of allowed values of parameters corresponding to an effective “mixed” hot-cold dark matter scenario of cosmological large scale structure formation. A combination of laboratory and astronomical test of the model is pointed out.

1. Cosmoarcheology

There are several possible links between the problems of Cosmoparticle Physics and space-time theory. First of all, the very foundations of cosmology and particle theory may find their unique basis in multidimensional theories of space-time, extending the ideas of Superstring theories, pretending to play the role of theories of everything. The main problem in developing a realistic theory of everything is the proper choice of its realization among the wide variety of possible versions, all reducing to the standard model and big bang cosmology in their extremely low energy limit. One may find some unique mathematical solution for the realistic variant, but even in this case a combination of indirect tests is necessary to prove that the solution is true. Such tests should combine indirect consequences of a true theory of everything, related to rare processes with elementary particles to be searched for at accelerators, exotic new astrophysical phenomena, new hypothetical forms of dark matter and nontrivial cosmological evolution, to be analyzed by the methods of CosmoParticle Physics.

To probe particular specific predictions of different

models of space-time, the methods of the branch of CosmoParticle Physics, named cosmoarcheology, can be applied. Cosmoarcheology, searching in astrophysical data for footprints of new physical phenomena in the Universe, may be viewed as an already existing branch of proper CosmoParticle Physics, in which all its components are mixed up in a nontrivial manner, resulting in a set of astrophysical tests for the existence and possible properties of hypothetical particles, fields, objects and phenomena predicted as cosmological consequences of particle theory. Cosmoarcheology treats the Universe as a unique natural accelerator laboratory, so that the astrophysical data play here the role of a specific experimental sample in Gedanken Experiments undertaken by Cosmoarcheology. As in any experiment, to achieve a meaningful result one should have precise understanding of the experimental device used, and, in addition, develop the methods of data sampling and analysis. The problem is that both the source and detectors in the Universal particle laboratory are out of control. Astrophysical processes cannot be directly reproduced in laboratories, but whatever complicated the combination of effects is, theoretical astrophysics, as a rule, uses in its analysis natural laws, proven by experiment. The trouble

¹e-mail: khlopov@khlopov.rc.ac.ru

is that, in a theoretical treatment of the Universe as a whole and its evolution, the basic physical laws are not known. Moreover, the picture, treated now in cosmology as a standard one, brings into consideration at least three elements, having physical grounds beyond the standard model of particle interactions. These fundamental elements are inflation, baryosynthesis and nonbaryonic dark matter, widely accepted by cosmologists but based on physical phenomena, having no direct experimental confirmation and implying experimentally unproven parts of particle theory. It makes a self-consistent formulation of the cosmoarcheological approach, in general, model dependent. One should account for the relationship between a hypothetical particle or field, probed by the astrophysical data, and the physics underlying the inflation, baryosynthesis and nonbaryonic dark matter. And, since the latter is model dependent, one should consider cosmological consequences of the hypothesis under study in the context of cosmological evolution, based on the chosen particle model, underlying these necessary elements of modern cosmology. That means that a cosmological trace of a hypothetical particle or field may be multi-step, following a nontrivial cosmological path implied by the model. On the other hand, one should expect, provided that the inflationary, baryon-asymmetric cosmology with nonbaryonic dark matter is indeed a proper basis of the Universe, the real picture of its evolution to be much more complicated than Gamow's original big bang Universe scenario, and generally more sophisticated than a simple addition of inflation, baryosynthesis and nonbaryonic dark matter dominance to the big bang scenario. The reason is that any physically plausible theoretical framework, giving rise to the necessary elements of cosmology, is generally much richer, supplementing these elements by a number of additional cosmologically relevant details. Testing these details, cosmoarcheology extends the might of observational cosmology, confronting the true theory of the Universe to observations.

One may take apart the cosmological necessities and turn to the cosmological impact of a true particle theory. Aesthetic arguments favor unification of fundamental forces. But the higher is the level of unification, the more extensive is the corresponding particle model and the larger hidden sector it implies. It brings into consideration more and more exotic cosmological implications, deserving serious attention in view of their physical motivations. There are more practical reasons to go beyond the standard model of particle interactions, recovering its internal theoretical inconsistencies. It also leads to specific cosmological effects, induced by cosmological consequences of the above extensions. In both cases one uses cosmoarcheology for astrophysical tests, but in unified models one has in principle a possibility of self-consistent treatment of cosmological evolution and new particle and fields effects, whereas separate considerations of some particular consequences of the particle model, used

generally in practical studies, lose the grounds of self-consistency. In the latter case astrophysical constraints should be critically analyzed and their accuracy and validity should be clearly specified.

2. Towards a true theory of the Universe

Assuming that inflationary baryon-asymmetric cosmology with nonbaryonic dark matter is closer to reality than Gamow's original big bang scenario, one should face the problem of observational evidence, specifying the choice of the inflationary model, mechanism of baryosynthesis and the proper form of nonbaryonic dark matter. In cosmoarcheology it is the problem of specifying the Universe as a natural accelerator.

Inflation. One considers inflation as a necessary element of the cosmological picture. Inflationary models explain, why the Universe expands. They provide solutions to the horizon, flatness, magnetic monopole, etc. problems. The solution is based on superluminal expansion, taking place for the equations of state $p < -1/3\varepsilon$. Neither matter, nor radiation dominance can provide such an equation of state. One needs some hypothetical phenomena to occur in the very early Universe, inducing an unstable negative-pressure stage of cosmological evolution. Such processes may be related to R^2 effects in gravity, to strong first-order phase transitions, or to slow rolling down of an effective potential to the true vacuum state. To make the proper choice between these possibilities, or, at least, to make some cut-off in their wide variety, additional traces of the inflationary mechanism should be considered.

Fluctuations on the inflationary stage induce a spectrum of initial density fluctuations, giving rise to galaxy and large scale structure (LSS) formation in respective scales. The amplitude of these fluctuations is constrained by the observed isotropy of the thermal electromagnetic background. It rules out all inflationary models with high amplitude of predicted fluctuations, in particular, most of GUT-induced phase transition scenarios. In the simplest models, with a quasi-de Sitter (close to $p = -\varepsilon$) equation of state at the inflationary stage, the flat Harrison-Zeldovich form of the spectrum is predicted. Then the estimated amplitude of initial fluctuations at the modern LSS scale provides some information on the possible inflaton properties, e.g., on the form and parameters of the scalar field potential.

For more complicated inflationary models, such as multicomponent inflation, the form of the predicted spectrum of fluctuations may differ from the simple flat one. Phase transitions at the inflationary stage lead to specific peaks or plateau in the spectrum with position and amplitude defined by the model parameters. One should also account for phase transitions after the global inflationary stage, able to modify the initial spectrum.

Both in R^2 and scalar field driven (e.g., chaotic) inflationary scenarios, there appears a long dust-like post-inflationary stage, induced by coherent inflaton field oscillations. The duration of such stages determines the maximum temperature of the Universe after reheating, when a radiation dominance stage starts. It also determines the specific entropy of the Universe after reheating.

The initial density fluctuations grow on the post-inflationary dust-like stage, following the general law of development of gravitational instability on a matter-dominated stage in expanding Universe $\delta\rho/\rho \propto t^{2/3}$. If the ratio of cosmological time scales, corresponding to the end, t_1 , and the beginning, t_0 , of the dust-like stage exceeds $\delta^{-3/2}$, where δ is the fluctuation amplitude, later on a scale inhomogeneity is formed. An evolution of such inhomogeneities may lead to primordial black hole (PBH) formation. The spectrum of PBHs reflects the scales, where the inhomogeneities are formed, as well as the mechanism of PBH formation. The minimal probability W_{PBH} of PBH formation is $\delta^{-13/2}$, estimated for direct formation of PBHs in contraction of a very small fraction of configurations, evolved from specific isotropic and homogeneous fluctuations. The account for PBH formation as a result of evolution of the bulk of inhomogeneities strongly increases the amount of expected PBHs.

Peaks in the spectrum of density fluctuations, produced at the inflationary stage, may also induce PBH formation even on the radiation-dominated stage with the probability $W_{\text{PBH}} \sim \exp(-1/18\delta^2)$.

Baryosynthesis. The generally accepted motivation for a baryon-asymmetric Universe is the observed absence of antimatter at macroscopic scales up to the scales of clusters of galaxies. In baryon-asymmetric models the observed baryonic matter originates from an initial baryon excess, surviving after local nucleon-antinucleon annihilation, occurring at the first millisecond of cosmological evolution. The baryon excess is assumed to be generated in the process of baryogenesis, resulting in baryon asymmetry of an initially baryon-symmetric Universe. It turned out that practically all the existing mechanisms of baryogenesis may under some conditions lead to inhomogeneous baryosynthesis and even to production of an antibaryon excess in some places. So inhomogeneities of baryon excess distribution and even domains of antimatter in the baryon asymmetric Universe may provide a probe for the mechanism of baryogenesis. In Sakharov's original baryosynthesis scenario, CP violating effects in out-of-equilibrium B -nonconserving processes, say, decays of some particles X , generated in a charge-symmetric Universe, with equal amount of X and their antiparticles, a baryon excess proportional to n_x and $\Im\phi$, ϕ being a CP violating phase. If the sign and magnitude of $\phi(x)$ vary in space, the same out-of-equilibrium B -nonconserving processes, leading to baryon asymmetry, results in $B(x)$ and in $B(x) < 0$ in the regions

where $\text{Im } \phi(x) < 0$. A spatial dependence of ϕ is predicted in the model of spontaneous CP violation or in models, where the CP violating phase is associated with the amplitude of an invisible axion field. The size and amount of antimatter in domains generated in this case, are related to the parameters of CP violation models and/or that of an invisible axion (see a review in [20]).

SUSY GUT motivated mechanisms of baryon asymmetry imply flatness of the superpotential due to the existence of a squark condensate. Such a condensate, being formed with $B > 0$, induces baryon asymmetry after squarks decay into quarks and gluinos. However, the mechanism does not fix the value and sign of B in the condensate, opening the possibilities for inhomogeneous baryon charge distribution and antibaryon domains.

The new approach to baryosynthesis, based on electroweak baryon charge nonconservation at high temperatures, also implies the possibility of antimatter domains, e.g., due to spontaneous CP violation.

So antimatter domains may appear in a baryon-asymmetric Universe and may be related to practically all mechanisms of baryosynthesis, CP violation mechanisms and to possible mechanisms of primordial baryon charge inhomogeneity. The domain sizes depend on the details of the respective phase transitions and initial distributions of the spatially variable CP violating phase, and due to inflation may be as large as the modern horizon, being the case for the models of "island Universe" with a very large-scale inhomogeneity of baryon charge distribution. The general parameters of the averaged effect of the domain structure are the relative amount of antimatter $\Omega_a = \rho_a/\rho_{\text{crit}}$, where ρ_a is the cosmological density of antimatter averaged over large scales, $\rho_{\text{crit}} = 3H^2/(8\pi G)$, the critical density, and the mean size of the domains, l (the characteristic scale in their distribution on sizes) or, for small domains, t_{an} , the time scale of their annihilation with the surrounding matter.

Nonbaryonic dark matter. The main arguments favoring a nonbaryonic nature of dark matter in the Universe, are the big-bang nucleosynthesis (BBN) in inflationary cosmology and the formation of large scale structure of the Universe under the observed isotropy of the relic radiation. The first line of argument points at the reasonable fits of BBN predictions to the observed light element abundances at $\Omega_B < 0,15 \div 0,20$ and the inflationary cosmology prediction $\Omega_{\text{tot}} = 1$, ascribing the difference to nonbaryonic dark matter. The second type of argument is that one cannot accommodate both the formation of the large scale structure and the observed isotropy of thermal electromagnetic background without some weakly interacting form of matter triggering the structure formation with minor effect upon the relic radiation angular distribution. There are several scenarios of structure formation by hot (HDM), cold (CDM), unstable (UDM), mixed

hot+cold (H+CDM), hierarchic decaying (HDS) dark matter, etc. These scenarios physically differ by the ways and succession of the structure element formation, as well as by the number of model parameters. But, keeping in mind the general independence of motivations for each type of dark matter candidates, one concludes that, from the particle physics viewpoint, the hot, cold, unstable, etc., dark matter scenarios are not alternatives, but rather supplementary options to be taken together, providing the whole set of reasonable physical arguments.

Indeed, one considers the would be eV-(10eV)- neutrino mass as a physical motivation for a hot dark matter scenario. But massive neutralinos, predicted in supersymmetric models, or invisible axions, following from the Peccei-Quinn solution of the strong CP violation problem in QCD, being cold dark matter candidates, rest on physical grounds which are by no means alternative to the physics of neutrino mass. So mixed hot+cold dark matter scenarios seem to be physically more reasonable than the simple one-parameter HDM or CDM models. However, all these motivations do not correlate with the problem of quark-lepton families, the existence of three types of neutrinos. Physical mechanisms of family symmetry breaking lead to new interactions, causing massive neutrino instability relative to decay into lighter neutrinos and light Goldstone boson, familon or singlet majoron. The neutrino instability, intimately related to family symmetry breaking, provides physical grounds for unstable dark matter (UDM) scenarios. At the expense of the additional parameter (unstable particles' lifetime), the UDM models eliminate the contradiction between the data on a total density within the inhomogeneities, $\Omega_{\text{inhom}} < 1$, and the inflationary cosmology prediction, $\Omega = 1$, ascribing the difference in Ω to a homogeneous background of unstable particles' decay products. The UDM models also recover the disadvantages of the HDM scenarios, related to the too rapid evolution of the structure after its formation. Owing to neutrino instability, a large scale structure, formed at redshifts corresponding to the observed distant objects, survives after the major part of dark matter, having formed the structure, decayed. The actual multicomponent content of dark matter may be still much richer, if one takes into account the hypothesis of shadow matter, following from the need to recover the equivalence of left- and right-handed coordinate frames in the Kaluza-Klein and superstring models. One faces the problem of accounting for the whole set of matter fields and interactions, arising from E'_8 , the sector of the heterotic string $E_8 * E'_8$ model. Even the above list of options, far from complete, poses the serious problem of a proper choice of a true combination of various dark matter candidates in physically motivated multicomponent dark matter scenarios.

Thus, since physical grounds for all the nonbaryonic dark matter candidates are outside the standard model and lose a proper experimental basis, we either

have to take into account all the possible ways to extend the standard model, treating all the candidates as independent ones, or find a quantitatively definite way to estimate their relative contribution.

3. Towards a true particle theory

Although the standard model of electroweak and strong (QCD) interactions does not face any direct experimental contradictions, there are several reasons to consider it to be incomplete and to seek its various extensions. Aesthetic arguments appeal to unified theories of fundamental forces of Nature, where the symmetry of the standard model should be extended to higher underlying symmetry, and the set of known particles should be completed to a full symmetry, using a large variety of particles and fields, forming a "hidden sector" of the corresponding model. The higher is the unification level, the wider is the "hidden sector" it needs to complete the underlying symmetry. However, attractive aesthetic reasons are, from the pragmatic viewpoint, less important than the need to eliminate the internal inconsistencies of the theory. So, supersymmetry is needed to remove the quadratic divergence of radiative corrections to the Higgs boson mass, while the axion is a solution to the CP violation problem in QCD. Such extensions of the standard model are usually considered separately, and, being related to different parts of particle theory, are generally treated independently. Note that it is just this type of physical motivation that is widely used to argue in favor of hot, cold, mixed, unstable,... dark matter candidates.

The cosmologically relevant consequences of both aesthetically and pragmatically motivated extensions of the standard model are generally related to stable or sufficiently metastable particles or objects predicted in them. So, since the (meta)stability is based in particle theory on some (approximate) conservation law, reflecting the corresponding fundamental symmetry and/or mechanism of symmetry breaking, cosmoarcheology probes the most fundamental new laws of Nature, assumed by new extensions of the standard model.

Indeed, new symmetries, extending the standard model symmetry, imply new charges, conserved exactly or approximately, and the lightest particle possessing such a charge should be either stable or metastable. The new charges may be related to local or global, continuous or discrete symmetry. They may be topological, induced by the topology of the relevant symmetry group. In most cases the mass of the hypothetic particles and objects reflects the scale where the assumed symmetry is broken.

- In all GUT models, unifying electromagnetism with other forces within a compact symmetry group, magnetic monopole solutions appear to be topological point objects, bearing the Dirac magnetic charge $g = hc/e$ and having the mass of the order Λ/e , where Λ is

the scale separated by the $U(1)$ symmetry, corresponding to electromagnetism, from the rest of interactions.

- Some specific GUT models imply the symmetry group topology, leading to the existence of domain walls (spontaneously broken discrete symmetry), cosmic string (spontaneously broken $U(1)$ symmetry), walls-surrounded-by-strings and other topological solutions. The corresponding energy density (per unit area or length) is of the order of the respective power of the symmetry breaking scale Λ , i.e. Λ for walls and Λ^2 for strings.

- The R symmetry (exact or approximate) in supersymmetric models protects the (meta)stability of the lightest supersymmetric particle (LSSP). Its mass is generally related to the scale of supersymmetry breaking. In local supersymmetric models this scale also defines the mass of gravitino, the supersymmetric partner of g graviton, having a semigravitational coupling to other particles, inversely proportional to the Planck scale m_{Pl} .

- The see-saw mechanism of neutrino mass generation results in a heavy right-handed neutrino with the Majorana mass M_R , related to the scale of lepton number nonconservation. The Majorana mass of an ordinary left-handed neutrino is m_D^2/M_R , where m_D is the Dirac mass of fermions (typically related to the mass of a charged lepton). The lifetime of a heavy right-handed neutrino, determined by its mixing with the left-handed one ($\propto m_D/M_R$), is inversely proportional to the mass of a light left-handed neutrino.

A spontaneous breaking of the Peccei-Quinn symmetry, used to eliminate the strong CP violation problem in QCD, results in the existence of a (pseudo)Goldstone boson, axion, with the mass $m_a \sim m_\pi f_\pi/F$, where F is the Peccei-Quinn symmetry breaking scale. The axion couplings to fermions are inversely proportional to F , and its lifetime relative to decay into 2γ is of the order of $64\pi F^2/m_a^3 \sim F^5$.

The equivalence of right- and left-handed coordinate systems implies the existence of mirror partners of ordinary particles. Mirror particles should not have ordinary gauge interactions and their own mirror interactions should be symmetric relative to interactions of the respective ordinary partners. Then mirror particles, having the same mass spectrum and the same internal mirror couplings as their ordinary partners, are coupled to the ordinary matter solely by gravity.

The inclusion of mirror particles along with the ordinary ones into a unifying GUT leads, after the GUT symmetry is broken and the ordinary and mirror sectors, retaining the discrete symmetry between them, are separated, to the existence of Alice strings, cosmic strings, changing the mutual mirrority of objects along the closed paths around them.

In superstring models the initial mirror symmetry is broken due to a combined action of compactification and gauge symmetry breaking, so that shadow matter appears, losing the discrete symmetry with the ordinary partners. In the heterotic string model the initial $E_8 * E'_8$ gauge symmetry, assuming exact symmetry between the ordinary (E_8) and mirror (E'_8) worlds in 10 space-time dimensional string model, is reduced after compactification and gauge symmetry breaking to a (broken) $E_6 * (\text{broken?}) E'_6$ 4-dimensional effective field model with the ordinary matter embraced by (broken) E_6 symmetry and the enormously extensive world of shadow particles and their interactions, corresponding to the $(\text{broken?}) E'_6$ gauge group.

The mechanism of gauge symmetry breaking in compactification into Calabi-Yao manifolds or orbifolds, used in superstring models, implies homotopically stable solutions with a mass $\propto r_c/\alpha'$, where r_c is the compactification radius and α' is the string tension. These objects are sterile relative to gauge interactions and may act on the ordinary matter only by gravity. These and many other examples of the particle zoo, induced by the extensions of the standard model of electroweak and strong interactions, are related to new phenomena, whose direct experimental search is either very hard, or impossible in principle.

So their cosmological effects are important or even unique sources of information on their possible existence.

4. Cosmoparticle physics of family symmetry breaking

The opposite way to a true theory of everything is to develop a realistic phenomenological framework putting together the standard model and the already known facts, finding theoretical grounds outside the standard model. Such an approach may be illustrated by the recently proposed model of horizontal unification (see [30] and references therein).

The problem of fermion families (generations) remains one of the central problems of particle physics. The standard $SU(3) * SU(2) * U(1)$ model, as well as its possible 'vertical' extensions (in the frames of a single generation) of the type $SU(5)$, $SO(10)$, etc., does not contain any deep physical ground both for the existence of mass hierarchy between generations and for the observed weak mixing of quarks and leptons owing to arbitrary Yukawa couplings. The identity of quark and lepton families

$$(u, d, e, \nu_e); \quad (c, s, \mu, \nu_\mu); \quad (t, b, \tau, \nu_\tau) \quad (1)$$

with respect to strong and electroweak interactions strongly suggests the existence of a "horizontal" symmetry between these generations. The concept of local horizontal symmetry $SU(3)_H$, first proposed in [1], might be reasonably considered with left-handed quark and lepton components transforming as $SU(3)_H$

triplets, and the right-handed ones transforming as antitriplets. Their mass terms transform as $3 * 3 = \bar{3} + 6$ and consequently may arise as a result of an $SU(3)$ breaking only. (A generalization to the case of n generations, $SU(n)$, is trivial.)

In this approach the hypothesis is reasonable, that the structure of these matrices is determined by the pattern of horizontal symmetry breaking (i.e., by the structure of vacuum expectation values (VEV) of horizontal scalars, maintaining the $SU(3)$ breaking) and the mass hierarchy between generations is related to a definite hierarchy in this breaking (the horizontal hierarchy hypothesis (HHH) [2, 3]).

The simplest realization of HHH invokes the introduction of additional superheavy fermions, acquiring their masses via direct coupling with horizontal scalars. The ordinary quark and lepton masses are induced by their "see-saw" mixing [3] with these heavy fermions.

The concept of grand unification (GUT) is another argument in favor of chiral G symmetry. In the GUT models left-handed quarks and leptons are put together with antiparticles of their right-handed component into the same irreducible representations of a GUT group G_{GUT} . So in the framework of $G_{GUT} * G_H$ symmetry the left-handed and right-handed components must transform as conjugated representations of G_H , i.e., the G_H symmetry must be chiral.

One may hope that a complete unification of horizontal and vertical symmetries will be achieved on the basis of a unifying fundamental symmetry G , including $G_{GUT} * G_H$ in the course of superstring theory development. Though the most elaborated simplest variant of the realistic superstring model [4, 5] $E_8 * E'_8$ leaves no room for including horizontal symmetry, such an inclusion is possible within the frames of a wider class of superstring models, e.g., in $SO(32)$ or in heterotic string models with a direct compactification to 4-dimensional space-time [6]. In the latter case [6] a wide class of GUT groups with ranks smaller than 22 is possible. The analysis of broken horizontal symmetry, given in the present paper, may be useful for the choice of realistic models from this variety of possibilities.

Here we do not consider supersymmetric extensions of the model, predicting a number of new particles, extending the hidden sector of the theory. The properties of such particles depend critically on the details of supersymmetry breaking and need a special detailed study.

To build a realistic model of broken horizontal symmetry, rather a wide set of parameters is to be introduced. However, (i) the number of these parameters is smaller than in realistic models without horizontal symmetry; (ii) the bulk of these parameters is fixed by the experimental data on the quark and lepton properties, and, finally, (iii) the set of new nontrivial physical phenomena predicted by the model, provides, in principle, a complete check of the model and determination of all the parameters. These new phenomena

arise at a high energy scale of horizontal symmetry breaking $> 10^5 - 10^6$ GeV, unachievable even in the remote future on accelerators. However, a combination of experimental searches of their indirect effects in processes with known particles with an analysis of their cosmological and astrophysical effects makes it possible to study the physics predicted at this scale.

The proposed model satisfies the following naturalness conditions:

a) Natural suppression of flavor changing neutral currents (FCNC) [7]. The light scalar $SU(2) * U(1)$ doublets, transformed by nontrivial representations of G_H (vertical-horizontal fields) and leading to unacceptably strong FCNC, are absent. The Yukawa couplings, responsible for quark and lepton mass generation, include the only standard $SU(2) * U(1)$ Higgs doublet, though the left- and right-handed fermion components transform as conjugate representations of the horizontal symmetry group. The price for it is the introduction of additional superheavy fermions, maintaining the hidden sector of the theory. The quark and lepton masses are induced by mixing with these heavy fermions. That is, the so called 'see-saw' mechanism [8] is realized not only for neutrinos, but for all quarks and leptons as well. Besides that, our approach provides a natural explanation for the hierarchy of electroweak and GUT scales on the basis of mechanisms suggested for GUT with one generation, e.g., by means of supersymmetric extensions of $SU(5)$, $SO(10)$ etc. [9]. Quark and lepton mass generation by means of vertical-horizontal fields would have needed unnatural fine tuning of their parameters even in the supersymmetric case.

(b) A natural horizontal hierarchy. The observed mass hierarchy of families (e.g., $m_e : m_\mu : m_\tau = 1 : 200 : 4000$, etc.) is explained by a much more moderate hierarchy of horizontal symmetry breaking. The parameters of such breaking are proportional to m for quarks and leptons. So there is no need for special mechanisms to protect the hierarchy from loop corrections;

(c) A natural solution to the QCD CP-violation problem [10]. Through there is only a single Higgs doublet, the theory provides a natural inclusion of $U(1)$ Peccei-Quinn symmetry [10], associated with heavy Higgs fields, breaking G by scale. Breaking of this global $U(1)$ symmetry results in the existence of a pseudo-Goldstone boson α of invisible axion type with the interaction scale [11] v_H . The α boson has both flavor-diagonal and flavor-nondiagonal coupling with quarks and leptons, i.e., is simultaneously a familon [12, 13]. Finally, it is related to neutrino Majorana mass generation, being in fact a majoron of singlet type [14].

The inevitable consequences of the model are:

(a) flavor changing neutral transitions, related to axion and horizontal gauge bosons interactions;

- (b) the existence of neutrino Majorana mass and neutrino mass hierarchy of families;
- (c) the instability of heavier neutrino with respect to axion decay into lighter neutrino;
- (d) the existence of metastable superheavy fermions.

The model may be checked in a combination of laboratory tests (a search for neutrino mass, for neutrino oscillations and for $2\beta_{0\nu}$ decay, studies of $\tilde{K}^0 - K^0$ and $\tilde{B}^0 - B^0$ transitions, a search for axion decays $\mu \rightarrow ea$, $K \rightarrow \pi a$ etc.) and the analysis of its cosmological and astrophysical predictions. The latter includes studies of axion emission effects on stellar evolution, investigation of a primordial axion field and massive unstable neutrino effects on the dynamics of cosmological large scale structure formation, as well as an analysis of the mechanisms of inflation and baryogenesis, based on the hidden sector of the model.

Theory of broken family symmetry

Consider the $SU(2) * U(1)$ model with a local chiral horizontal $SU(3)_H$ symmetry [1, 15] between the families (1). Quarks and leptons are put into the following representations of $SU(2) * U(1) * SU(3)_H$:

$$f_{L\alpha} : \begin{pmatrix} u \\ d \end{pmatrix}_{L\alpha} (2, 1/3, 3), \quad \begin{pmatrix} \nu \\ e \end{pmatrix}_{L\alpha} (2, -1, 3)$$

$$f_R^\alpha : u_R^\alpha(1, 4/3, \tilde{3}), \quad d_R^\alpha(1, -2/3, \tilde{3}), \quad e_R^\alpha(1, -2, \tilde{3})(2)$$

where we retain the family ($SU(3)_H$) index: $\alpha = 1, 2, 3$.

We can choose scalars, breaking the horizontal symmetry, such as $SU(3)_H$ sextets and triplets. All of them are to be $SU(2) * U(1)$ singlets, to prevent electroweak symmetry breaking of the $SU(3)_H$ scale. To generate realistic quark and lepton mass matrices, at least three such ‘‘horizontal’’ scalars are needed. At least one of them with the greatest VEV is to be a sextet: $\xi_{\alpha,\beta}^{(0)}$, $\alpha, \beta = 1, 2, 3$. Otherwise, triplet fields alone do not generate realistic mass matrices. For the other two scalars $\xi^{(1)}$ and $\xi^{(2)}$, one may further specify their $SU(3)$ content, only those cases are to be mentioned when the sextet and triplet representations result in different consequences.

Let us introduce additional fermions in the form [3, 15]

$$F_L^\alpha : U_L^\alpha(1, 4/3, \tilde{3});$$

$$D_L^\alpha(1, -2/3, \tilde{3}); \quad E_L^\alpha(1, -2, \tilde{3})$$

$$F_{R\alpha} : U_{R\alpha}(1, 4/3, 3); \quad D_{R\alpha}(1, -2/3, 3);$$

$$E_{R\alpha}(1, -2, 3); \quad N_{R\alpha}(1, 0, 3) \quad (3)$$

Note that these fermions cancel the $SU(3)_H$ anomaly of quarks and leptons (2). The most general Yukawa couplings allowed by the symmetry are

$$g_f \tilde{f}_{L\alpha} F_{R\alpha} \phi^0 + G_F^{(n)} \tilde{F}_L^\alpha F_{R\beta} \tilde{\xi}^{(n)\alpha\beta}$$

$$+ G_\eta \tilde{F}_L^\alpha f_R^\alpha \eta + h.c.; \quad n = 0, 1, 2 \quad (4)$$

for quarks and leptons [3, 15] ($f = u, d, e$; $F = U, D, E$) and

$$g_\nu \tilde{\nu}_{L\alpha} N_{R\alpha} \phi^0 + G_N^{(n)} N_{R\alpha} C N_{R\beta} \tilde{\xi}^{(n)\alpha\beta} + h.c. \quad (5)$$

for neutrinos [15, 16]. Here ϕ^0 is the neutral component of the standard $SU(2) * U(1)$ Higgs doublet $(2, -1, 1)$ ($\langle \phi^0 \rangle = v = (\sqrt{8}G_F) = 250 \text{ GeV}$) and η is a real $SU(2) * U(1) * SU(3)_H$ singlet scalar ($\langle \eta \rangle = \mu/G_\eta$)

The Yukawa couplings (4),(5) are invariant under global axial $U(1)_H$ transformations:

$$f_L \rightarrow f_L \exp(i\omega), \quad f_R \rightarrow f_R \exp(-i\omega),$$

$$F_L \rightarrow F_L \exp(-i\omega) F_R \rightarrow F_R \exp(i\omega),$$

$$\phi \rightarrow \phi, \quad \xi^{(n)} \rightarrow \xi^{(n)} \exp(2i\omega); \quad n = 0, 1, 2. \quad (6)$$

This $U(1)$ symmetry will be maintained also by the Higgs potential, provided that there are trilinear couplings such as $\Lambda \xi_{\alpha\beta}^{(0)} \xi^{(1)\alpha} \xi^{(1)\beta} + h.c.$, etc. These couplings are not induced by any other (gauge or Yukawa) interactions. So their absence in the Lagrangian is natural [15, 16].

The analysis of the Higgs potential (see [2, 15, 16] for details) shows, that the VEV matrix can acquire the form:

$$V_H = \langle \xi^{(0)} + \xi^{(1)} + \xi^{(2)} \rangle$$

$$= \begin{pmatrix} r_1 & p_1 & p_3 \\ +(-)p_1 & r_2 & p_2 \\ +(-)p_3 & +(-)p_2 & r_3 \end{pmatrix} \quad (7)$$

(where the ‘+’ and ‘-’ signs correspond to the sextet and triplet, respectively) with the natural 5-10-fold hierarchy of their values:

$$r_1 > p_1 > r_2 > p_2 > p_3 > r_3 \quad (8)$$

Inserting the scalar VEVs into the Yukawa couplings (4),(5), one obtains the full 6*6 fermion mass matrices:

$$\begin{pmatrix} f_R & F_R \\ \tilde{f}_L & \begin{pmatrix} 0 & g_f v \\ \mu & M_F \end{pmatrix} \end{pmatrix}; \quad \begin{pmatrix} \nu_R & N_R \\ \tilde{\nu}_L & \begin{pmatrix} 0 & g_\nu v \\ g_\nu v & M_N \end{pmatrix} \end{pmatrix} \quad (9)$$

Here $M_F = \Sigma \langle \xi^{(n)} \rangle G_F^{(n)}$, $F = U, D, E, N$; and $N_L = C \tilde{N}_R$, $\nu_R = C \tilde{\nu}_L$. Note that only sextet scalars contribute into the Majorana mass matrix M_N . So, one has a Dirac ‘‘see-saw’’ mechanism of quark and lepton mass generation and an ordinary Majorana ‘‘see-saw’’ mechanism for the neutrino mass term where $N_{R\alpha}$ play the role of right-handed neutrino. The quark and lepton mass matrices, obtained from the block-diagonalization of (9), will have the form:

$$m_f = g_f v \mu M_F^{-1}; \quad f = u, d, e; \quad m_\nu = (g_\nu v)^2 M_N^{-1} \quad (10)$$

So the mass hierarchy between the families appears to be inverted with respect to the hierarchy of the $SU(3)_H * U(1)_H$ symmetry breaking:

$$SU(3)_H * U(1)_H [v_H \sim r_1]$$

$$\rightarrow SU(2)_H * U(1)'_H [v'_H \sim p_1]$$

$$\rightarrow U(1)''_H [v''_H \sim p_2] \rightarrow I \quad (11)$$

Here the intermediate $SU(2)_H * U(1)'_H$ horizontal symmetry is maintained between the second and the third generations of quarks and leptons: the remaining global $U(1)''_H$ is appropriate to the third generation only. The case under consideration is called the inverse hierarchy model, in contrast with the direct hierarchy model, where the quark and lepton mass hierarchy is parallel to hierarchy of $SU(3)_H * U(1)_H$ symmetry breaking [15, 17]. The global $U(1)_H$ ($U(1)''_H$) symmetry breaking results in the existence of a massless Goldstone boson, a , named archion, having both flavor-diagonal and flavor-nondiagonal couplings to quarks and leptons and thus being a familon of the type [13, 18]. For the sextet $\xi^{(1)}$ and $\xi^{(2)}$, its main couplings with, e.g., charged leptons have the form

$$-ia(g_{\tau\tau}\tilde{\tau}\gamma_5\tau + g_{\tau\mu}\tilde{\tau}\gamma_5\mu + g_{\tau e}\tilde{\tau}\gamma_5e + g_{\mu\mu}\tilde{\mu}\gamma_5\mu + g_{\mu e}\tilde{\mu}\gamma_5e + g_{ee}\tilde{e}\gamma_5e) + h.c \quad (12)$$

where

$$\begin{aligned} g_{\tau\tau} &= m_\tau/v_H'', & g_{\tau\mu} &\approx m_{23}^l/v_H'', \\ g_{\tau e} &\approx m_{13}^l/v_H'', & g_{\mu\mu} &< m_\mu/v_H', \\ g_{ee} &< (m_e/m_\tau)(m_l/v_H''), \\ g_{e\mu} &< (m_\mu/m_\tau)^{1/2}(m_{12}^l/v_H''). \end{aligned}$$

For the triplet $\xi^{(1)}$ and $\xi^{(2)}$, the flavor nondiagonal coupling are scalars. In the tree approximation the couplings of a with quarks are similar to (12). In our minimal $SU(2) * U(1) * SU(3)_H$ model a is the particle of the arion type [19]. It has no couplings $a\gamma\gamma$ and agg induced by triangle diagrams. Its interactions with the ordinary matter are suppressed sufficiently to eliminate the strong astrophysical restrictions [20] on the scale v_H'' . So the flavor changing decays may go with noticeable probability [15, 21], e.g.,

$$\begin{aligned} \mu &\rightarrow ea, & \tau &\rightarrow \mu a, & K &\rightarrow \pi a, \\ B &\rightarrow K(K^*)a, & D &\rightarrow \pi(p)a, \\ \Lambda &\rightarrow na, & \Lambda_b^0 &\rightarrow \Lambda a, & \Lambda_b^0 &\rightarrow na \end{aligned} \quad (13)$$

A search for such decays could provide valuable information on the structure of fermion mass matrices.

In any realistic extension of our scheme, e.g., in $SU(5) * SU(3)_H$ model, triangle diagrams owing to the inevitable presence of additional heavy fermions (GUT) induce $a\gamma\gamma$ and agg vertices, so that $U(1)''_H$ turns to be a Peccei-Quinn symmetry [10] and the archion becomes an invisible axion of nearly hadronic type [22]. The scale $v_H'' = v_{PQ}$ is then restricted from below by astrophysical estimations of stellar energy losses due to archion emission: $v_{PQ} > 10^6$ GeV (the Sun and red giants [23, 20, 15] and $v_{PQ} > 10^{10}$ GeV (Supernova SN1987A [24]). The latter restriction seems to be taken with caution.

According to (10), the hierarchy of neutrino Majorana masses is similar to the ordinary quark and lepton mass hierarchy: $m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} \sim m_e : m_\mu : m_\tau$. For the sextet $\xi^{(1)}$ and $\xi^{(2)}$ the neutrino mass matrix

m_ν (10) is nondiagonal and archion decays are possible with the lifetimes $\tau(\nu_H \rightarrow \nu_L a) = 16\pi/g_{HL}^2 m_H$, where $g_{HL} = g_{\nu_H \nu_L} = m_{HL}/v_{PQ}$.

For "small" scale of family symmetry breaking $v_{PQ} \sim 10^6$ GeV the predicted effect of Majorana masses of neutrino is rather close to the modern sensitivity of $2\beta_{0\nu}$ searches.

Since the archion couplings to fermions of the lightest family (u, d, e) are suppressed, the existing constraints on the corresponding scale are weakened to $v_{PQ} > 10^6$ GeV, making the model of archion rather close to the hadronic axion model [22]. However, it turns out [25] that the archion model escapes the serious problem of primordial superheavy stable Q quarks, predicted in the hadronic axion model [25, 22, 26]. One can estimate the frozen concentration of Q quarks and respective Q hadrons in the Universe and find it to contradict [25] the upper limits on such concentration, following from the search for anomalous nuclei (so called "crazy isotopes"). So the theory should introduce a mechanism of superheavy quark instability. But the inclusion of the hadronic axion model into GUT models leads inevitably to the existence of a superheavy lepton coupled to axion. Then, the mixing of superheavy quark Q with the light (ordinary) quarks, inducing a Q instability, would lead to the existence a tree-level axion coupling to leptons, so that the axion is not hadronic. In view of these troubles of the hadronic axion model, the archion model is of special interest, since it naturally provides both superheavy quark instability and the suppression of an axion coupling to leptons.

The set of restrictions upon free model parameters

So two groups of new parameters have been introduced in the model:

- (*) VEVs of "horizontal" Higgs fields $\langle \xi_i \rangle$ (F''', F', F) and
- (**) Yukawa couplings of fields ξ_i to additional fermions ($p_i, i = 1, 2, 3$).

However, the amount of free parameters is actually smaller as compared with the standard model due to the relationships between the parameters, imposed by both the symmetry and the reproduction of observed mass matrices for quarks and leptons

$$F : F' : F''' \simeq 1 : 30 : 200. \quad (14)$$

The structure of the mass matrices of quarks and leptons is explained in the model under consideration by the hierarchy of horizontal symmetry breaking (1), and not by the great difference in Yukawa couplings for different generations as it is in the standard model.

The remaining free parameters are fixed by the following system of laboratory and cosmological restrictions:

- (a) The data on $\mu \rightarrow ea$ and $K \rightarrow \pi a$ decays lead to the lower bound $F > 4 \cdot 10^5$ GeV [15].

(b) The astrophysical estimations of stellar energy losses due to archion emission (for stars of the main sequence and red giants) give rise to the next lower bound $F \geq 10^6 \text{ GeV}$ [6]. This bound turns out to be by two orders of magnitude weaker than that in the case of invisible axions owing to suppression of archion coupling to the lightest family fermions (u, d, e).

(c) Archion emission can affect the time scale and energetics of neutrino flux from collapsing stars. An analysis of such a possible influence for SN1987 excludes the interval $10^6 \text{ GeV} \leq F \leq 3 \cdot 10^9 \text{ GeV}$ [27, 28].

(d) Generation of density perturbations in the phase transitions with family symmetry breaking at the inflationary stage has been analyzed in [29]. The observed isotropy of the relic radiation and astronomical restrictions on the concentration of primordial black holes in the Universe make it possible to exclude (in the model of multicomponent chaotic inflation) the values $F > 10^{11} \text{ GeV}$ on the scale of family symmetry breaking.

(e) As shown in [30], the initial distribution of θ changing by 2π around a string implies an inhomogeneity of the amplitude of coherent axion field oscillations with respect to the true vacuum, proportional to $\theta - \theta_{vac}$, where $\theta_{vac} = 2\pi n$ with n integer. The large scale distribution of these primordial inhomogeneities, named archioles, reflects the vacuum axion walls-surrounded-by-strings structure, formed when the axion mass is "switched on" at $T \sim 800 \text{ MeV}$. Owing to a superweak self-interaction of the invisible axion, the vacuum walls-and-strings structure and archioles split, and their successive evolution goes separately. The vacuum walls-surrounded-by-strings structure is known to disappear rapidly due to gravitational radiation, and the large-scale structure of archioles freezes out on the radiation dominance stage. Archioles reflect the original Brownian nature of axion strings, having on each scale about 80% of string length in the form of infinite strings, stretching out of regions of the relevant size [31]. So the archioles form a fractal structure, causing inhomogeneities on all scales. Putting aside the small-scale evolution of archioles, speculations [30] show that large scale inhomogeneities induced by archioles cannot be smaller than $\delta \sim 10^{-2}(F/10^{10} \text{ GeV})$, causing a new phenomena for the cosmological models with even small axionic dark matter admixtures at $F > 10^8 \text{ GeV}$. According to [27], at $F < 10^8 \text{ GeV}$ coherent axion field oscillations are thermalized due to $aN(\tilde{N}) \rightarrow \pi N(\tilde{N})$ reactions, so that the archioles structure dissipates. The primordial axion field distribution can in this case induce a fractal distribution of baryonic charge. If the arguments [30] are true and archioles really cause troubles for the axionic CDM scenario, one obtains the constraint $F < 10^8 \text{ GeV}$.

(f) Since the neutrino mass is proportional to p/F , its lifetime $\tau \sim F^5$ and the primordial axion field density $\rho_a = \bar{\rho} \sim F$ [32]; at larger F the axion field is to

dominate in the Universe, the massive stable neutrino dominance corresponds to smaller F , and, finally, the smallest possible F correspond to cosmological models with massive unstable neutrino [32, 33, 27]. So changing the parameter F , one reproduces all the main types of cosmological models for the formation of the structure of the Universe. In our approach a continuous change of F results in a continuous transition from one to another form of dark matter dominating in the Universe and in definite predictions of the model for each type of dark matter, corresponding to the combination of respective cosmological, astrophysical and physical constraints. Indeed, due to the presence of the Majorana neutrino masses with the hierarchy [15]

$$m_{\nu_e} : m_{\nu_\mu} : m_{\nu_\tau} \simeq m_e : m_\mu : m_\tau \quad (15)$$

of archion and neutrino transitions with archion emission

$$\nu_\tau \rightarrow \nu_\mu a; \quad \nu_\mu \rightarrow \nu_e a, \quad (16)$$

the total cosmological density ρ_{tot} and hence the density ρ_B being fixed, the relationship [25]

$$\rho_a^{\text{prim}} + \sum \rho_{\nu_i}^{\text{prim}} + \rho_a^{\text{dec}} + \rho_B = \rho_{tot} \quad (17)$$

turns out to be an equation with respect to F and the couplings p_i (assumed to be of the same magnitude for all generations). Solutions to this equation define a discrete set of cosmological models with different types of dark matter [25]. The solutions exist only if $p \leq 1,5 \cdot 10^{-4}$. For larger values of p the predicted dark matter density exceeds the total cosmological density.

The discrete set of solutions to Eq. (17), depending on F and h , reproduces in a quantitatively definite way all the main types of popular dark matter scenarios CDM, HDM, mixed CDM+HDM, relativistic and nonrelativistic UDM. They are:

The set of dark matter models

1. Archion coherent oscillations dominance as CDM. The cosmological evolution of the archion field after Peccei-Quinn symmetry breaking implies in our approach the general features of the standard model of "invisible" axions. The $SU(3)_H * U(1)_H$ symmetry breaking leads F to be in fact Peccei-Quinn symmetry of only one quark-lepton generation, that resolves automatically the cosmological θ -domain problem in the axion theory [34]. The modern archion mass density is equal to

$$\rho_a = (F/4 \cdot 10^{12} \text{ GeV}) \rho_{cr}, \quad \rho_{cr} = \frac{3H^2}{8\pi G} \quad (18)$$

Taking into account the intensive archion emission by a decaying archion cosmic string structure results in a growth of modern cosmological axion density up to

$$\rho_a = (F/2 \cdot 10^{10} \text{ GeV}) \rho_{cr}. \quad (19)$$

2. Hot dark matter (HDM) scenario. The dominance of ν_τ with the standard concentration $n_\nu = 3/11n_\gamma$, the mass $m_{\nu_\tau} = 20\text{eV}$ and a lifetime exceeding the age of the Universe, t_U , ($t_U < \tau(\nu_\tau \rightarrow \nu_\mu a)$):

$$\rho_{\nu_\tau} = \frac{6,6 \cdot 10^{13} \text{GeV}}{F} h \rho_{\text{cr}}. \quad (20)$$

3. Relativistic unstable dark matter (UDM) scenario. The Universe dominated by relativistic archions and ν_μ , the products of $\nu_\tau \rightarrow \nu_\mu a$ decay with the mass $m_{\nu_\tau} = 50 - 100\text{eV}$ and lifetime $\tau(\nu_\tau \rightarrow \nu_\mu a) = 4 \cdot 10^{15} - 10^{16}\text{s}$ ($m_{\nu_\mu} < 5\text{eV}$):

$$\rho_{\nu_\mu+a}^{\text{rel}} = \frac{(F/10^{10} \text{GeV})^{3/2}}{p^{1/2}} \cdot \rho_{\text{cr}} \quad (21)$$

4. Nonrelativistic UDM scenario. The dominance of nonrelativistic ν_μ with the mass $\sim 10\text{eV}$, both primordial and from $\nu_\tau \rightarrow \nu_\mu a$ decay of ν_τ with the mass $\sim 100\text{eV}$ and lifetime $\sim 10^{15}\text{s}$, provided that $\tau(\nu_\mu \rightarrow \nu_e a) > t_U$:

$$\rho_{\nu_\mu} = \frac{0.6 \cdot 10^{12} \text{GeV}}{F} p \rho_{\text{cr}} \quad (22)$$

5. Relativistic hierarchic decay (HD) scenario. The dominance of relativistic archions ρ_a^{dec} and ν_e in the modern Universe, from decay of ν_μ with the mass $m_{\nu_\mu} = 50 - 100\text{eV}$ and lifetime $\tau(\nu_\mu \rightarrow \nu_e a) = 4 \cdot 10^{15} - 10^{16}\text{s}$, under the condition of rapid decay of ν_τ with the mass $m_{\nu_\tau} \sim (1 - 10)\text{keV}$, $\tau(\nu_\tau \rightarrow \nu_\mu a) < (10^8 - 10^{10})\text{s}$:

$$\rho_{\nu_e+a}^{\text{rel}} = \frac{(F/10^8 \text{GeV})^{3/2}}{p^{1/2}} \rho_{\text{cr}} \quad (23)$$

6. Nonrelativistic HD scenario. The dominance of nonrelativistic or semirelativistic archions, originated from both early ν_τ decay and successive ν_μ decays, provided that $m_a > m_{\nu_e}$. Or, in the other case ($m_a < m_{\nu_e}$) the dominance of nonrelativistic ν_e , both primordial and from ν_τ and ν_μ decays:

$$\rho_{\nu_e} = \frac{3,3 \cdot 10^{10} \text{GeV}}{F} p \rho_{\text{cr}} \quad (24)$$

In the former case the main contribution into the inhomogeneous dark matter (in rich galaxy clusters and halos of galaxies) is provided by both a primordial thermal archion background and nonrelativistic archions from early ν_τ decays

$$\rho_a = \frac{9 \cdot 10^4 \text{GeV}}{F} \rho_{\text{cr}} \quad (25)$$

Putting together the restrictions (a)—(f), the space of the model parameters is reduced to the only possible narrow window in the vicinity of

$$F = F_6 = 10^6 \text{GeV} \quad \text{and} \quad p = 5 \cdot 10^{-7} - 5 \cdot 10^{-6} \quad (26)$$

This solution corresponds to hierarchic decay scenario, sharing the qualitative advantages of the CDM, HDM

and UDM models. It was also shown that the model contains physical grounds for inflation and baryosynthesis and may be viewed as a quantitatively definite phenomenology for theories of everything [35].

Hierarchic decay scenario

In the hierarchic decay scenario (HDS) the large scale structure formation takes place as a result of the stages of dominance of unstable massive neutrinos and their relativistic decay products. In the period from $t_0 = 10^6 (1\text{keV}/m_{\nu_\tau})^2\text{s}$. to $\tau_{\nu_\tau}(\nu_\tau \rightarrow \nu_\mu a) = 10^{10} (1\text{keV}/m_{\nu_\tau})^3\text{s}$. the Universe is ν_τ dominated. The mass of ν_τ is disposed in the range $m_{\nu_\tau} = 1 - 10\text{keV}$ (according to (2.13)). Its decay at $t = \tau_{\nu_\tau}$ leads to the period of relativistic ν_μ and a dominance and to the subsequent period of ν_μ dominance with the mass $m_{\nu_\mu} = 0,1 - 1\text{keV}$. At $t = \tau_{\nu_\mu}(\nu_\mu \rightarrow \nu_e a) = 10^{16} (1\text{keV}/m_{\nu_\tau})^3\text{s}$. the $\nu_\mu \rightarrow \nu_e a$ decays slow down the rate of the structure evolution and thus provide its survival to the present time.

So the UDM scenario is realized in this case. In the modern Universe the dominant DM types are thermal primordial archions [6] with the mass $m_a = 3\text{eV}$ and number density $n_a = 0,6n_\nu$ and archions from the ν_τ and ν_μ decays, as well as ν_e with the mass $m_{\nu_e} = 1\text{eV}$, both primordial and from ν_μ decays.

Note that the HD scenarios 5 and 6 combine the attractive features of the HDM, CDM and UDM models. This makes the HD scenarios an appealing physically relevant theoretical basis for detailed models of the cosmological large scale structure formation and for comparison of the predictions of such models with the astronomical data. Indeed, in the HD scenarios the dominance of ν_τ with the mass (1-10)keV in the period ($10^8 - 10^{10}$)s induces short-wave fluctuations in the spectrum of density perturbations of ν_μ with the mass (50-100)eV. ν_μ from $\nu_\tau \rightarrow \nu_\mu a$ decays enhance in this spectrum (by the factor of 2) the long-wave component, inherent to HDM models, providing the formulation of clear cellular structure of voids and superclusters. Finally, $\nu_\mu \rightarrow \nu_e a$ decays at $t \sim (10^{15} - 10^{16})\text{s}$ slow down the rate of the evolution of the structure and provide its survival to the present time. The primordial thermal archion background, being in these models the coldest component of the modern dark matter, play an important role in the evolution of the shortest wavelength part of density perturbations, inducing, in particular, the formation of massive halos outside the visible parts of galaxies. One should keep in mind that, according to [36], the phase space restrictions on the mass of halo particles [37] can be weakened or even completely eliminated in the case of a Bose gas.

A quantitative analysis of the HD scenario was initiated recently by ourselves with Doroshkevich and Berezhiani on the basis of a linear theory of density perturbation spectrum evolution, given by

$$P(k, t_f) = (b(t_i)/b(t_f))^2 T^2(k, t_f) P(k, t_i) \quad (27)$$

where $P(k, t_i)$ is the spectrum of initial perturbations and $T(k, t_f)$ is the transfer function describing the spectrum evolution DM model under study; $b(t)$ specifies the linear growth law of long-wavelength perturbations. An evaluation of the transfer function assumes in general a solution of the kinetic Vlasov equation in the gravitation field for the relevant dark matter model. Here, instead, we will approximate the transfer functions by reasonable modification of the standard transfer functions for CDM and HDM models, given in [38]:

$$\begin{aligned} T_{\text{CDM}}(k) &= \frac{\ln(1 + 2,34q)}{2,34q} (1 + 3,89q \\ &+ (16,1q)^2 + (5,46q)^3 + (6,71q)^4)^{-1/4}; \quad (28) \\ T_{\text{HDM}}(k) &= \exp(-0,16(kR_{f\nu}) \\ &- (kR_{f\nu})^2/2)(1 + 1.6q + (4.0q)^{3/2} + (0.92q)^2)^{-1}; \quad (29) \\ q &= k/\Omega_\nu h^2 (\text{Mpc})^{-1} \quad R_{f\nu} = 2.6(\Omega_\nu h^2)^{-1} \text{Mpc}; \\ \Omega_\nu h^2 &= 0.31 m_\nu / (30 \text{ eV}) \end{aligned}$$

where $h = H_0/100 \text{ km/s/Mpc}$ and H_0 is the present Hubble constant.

The evolution of perturbations in the hierarchic decay scenario proceeds according to the following scheme:

The period of dominance of ν_τ induces short wave fluctuations in the spectrum of density perturbations, inherent to the CDM model (more precisely, to warm dark matter). In this period the derelativization of ν_μ makes their perturbations to share the same form of the spectrum, so that the short-wave fluctuations retain after $\nu_\tau \rightarrow \nu_\mu a$ decays. In addition to these density fluctuations, the ones of ν_μ from ν_τ decays enhance the long-wave component of the spectrum. ν_μ decays slow down the structure evolution rate and provide its survival to the present time. The hierarchy of lifetimes of ν_τ and ν_μ , which inevitably follows from the hierarchy (1), leads to the respective hierarchy of scales. Thus, the transfer function to the period of $\nu_\mu \rightarrow \nu_e a$ decay will be a sum of two transfer functions: the one of the primordial $\nu_{\mu 1}$ and the one of $\nu_{\mu 2}$ from $\nu_\tau \rightarrow \nu_\mu a$ decays:

$$T_{\text{HDS}}(k) = (T_{\nu_{\mu 1}}^2(k) + T_{\nu_{\mu 2}}^2(k))^{1/2} / \sqrt{2} \quad (30)$$

We will denote these functions $T_{\nu_{\mu 1}}$ and $T_{\nu_{\mu 2}}$, respectively. Before the derelativization of primordial $\nu_{\mu 1}$ at $t_{\nu_{\mu 1}} = 10^8 (\text{keV}/m_{\nu_\tau})^2$ the perturbations in the ν_τ gas evolve similar to the HDM and the transfer function has the form (29). In the period from the moment $t_{\nu_{\mu 1}}$ to the moment $\tau_{\nu_\tau} = 10^{10} (\text{keV}/m_{\nu_\tau})^3$, when ν_τ decay, the derelativization of $\nu_{\mu 1}$ takes place, inducing ν_τ scale fluctuations and the transfer function will be T_* in this period. After ν_τ decays until the moment of ν_μ decays, the perturbations in the primordial $\nu_{\mu 1}$ evolve according to the CDM scenario and the transfer function of this period has the form (3.2). Thus, the resulting transfer function for the primordial $\nu_{\mu 1}$ at

the moment of ν_μ decays $t = \tau_{\nu_\mu}$ is a product of the three functions:

$$T_{\nu_{\mu 1}} = T_{\text{HDM}}^{\nu_\tau} T_* T_{\text{CDM}} \quad (31)$$

with the following parameters, determined at $t = \tau_{\nu_\mu}$ as

$$\begin{aligned} \Omega_{\nu_\tau} h^2 &= 10.3 (m_{\nu_\tau} / 1 \text{ keV}); \\ R_{f\nu_\tau} &= 3 \cdot 10^{-2} (1 \text{ keV}/m_{\nu_\tau})^3. \end{aligned} \quad (32)$$

To specify the form of the transfer function T_* , consider now the mechanism of shortwave fluctuation generation in the gas of derelativized primordial $\nu_{\mu 1}$ at the stage of unstable ν_τ dominance. At this stage the perturbations in the gas of primordial $\nu_{\mu 1}$ grow on the scales $R > R_{\nu_{\mu 1}}$ according to the following equation [39]:

$$\ddot{\delta}_{\nu_{\mu 1}} + 4\dot{\delta}_{\nu_{\mu 1}}/3t \approx 4\pi G \rho_{\nu_\tau} \delta_{\nu_\tau} = 2\delta_{\nu_\tau}/3t^2 \quad (33)$$

where $R_{\nu_{\mu 1}}$ is the Jeans length of $\nu_{\mu 1}$, $\delta_{\nu_{\mu 1}}$ and δ_{ν_τ} are the density contrasts in the gas of $\nu_{\mu 1}$ and ν_τ , respectively. The solution to (12) is [39]

$$\delta_{\nu_{\mu 1}}(\theta) = \delta_{\nu_\tau}(t_{\nu_{\mu 1}})(\theta^{2/3} + 2\theta^{-1/3} - 3) \quad (34)$$

where $\theta = t/t_{\nu_{\mu 1}}$.

The Jeans length of relic $\nu_{\mu 1}$ is given by

$$R_{\nu_{\mu 1}}(t) = \langle v \rangle_{\nu_{\mu 1}} t \approx c T_{\nu_{\mu 1}} t / m_{\nu_\mu} = c t_{\nu_{\mu 1}}^{2/3} t^{1/3} \quad (35)$$

For scales $R > R_{\nu_{\mu 1}}(t)$ the perturbations in the $\nu_{\mu 1}$ grow according to (34), until the R exceeds the $R_{\nu_{\mu 1}}(t)$, growing with time according to (35). Since the scale factor grows in this period as $\propto t^{2/3}$, it means that the properties of ν_τ gas fluctuations are shared by $\nu_{\mu 1}$ gas on less and less massive scales. The smallest mass scale of $\nu_{\mu 1}$ perturbations corresponds to the length $R = R_{\nu_{\mu 1}}(\tau_{\nu_\tau})$.

Thus one can find that the transfer function T_* for the gas of primordial ν_μ can be written as follows:

$$\begin{aligned} T_* &= ((kR_{\nu_{\mu 1}}^H)^{-2} + 2kR_{\nu_{\mu 1}}^H - 3)^{1/2} \\ &\text{for } k > R_{\nu_{\mu 1}}^{-1}(\tau_{\nu_\tau}), \\ T_* &= 4,5 (\text{keV}/m_{\nu_\tau}) \\ &\text{for } k < R_{\nu_{\mu 1}}^{-1}(\tau_{\nu_\tau}) \end{aligned} \quad (36)$$

Here $R_{\nu_{\mu 1}}^H$ is the horizon size at the moment $t_{\nu_{\mu 1}}$. At the moment of ν_μ decay $t = \tau_{\nu_\mu}$, the scales in Eq. (36) are equal to

$$\begin{aligned} R_{\nu_{\mu 1}}^H &= 10^{-2} (\text{keV}/m_{\nu_\tau})^2 \text{ Mpc}. \\ R_{\nu_{\mu 1}} &= 4,6 \cdot 10^{-2} (\text{keV}/m_{\nu_\tau})^3 \text{ Mpc}. \end{aligned} \quad (37)$$

Assuming that the $\nu_\tau \rightarrow \nu_\mu a$ decay proceeds instantaneously at $t = \tau_{\nu_\tau}$, we can use Eq. (29) for the transfer function of $T_{\nu_{\mu 2}}$, with a proper correction for the scale. Namely, we must renormalize the scale because $\nu_{\mu 2}$ from ν_τ decays turn out to be nonrelativistic at the moment $t_{\nu_{\mu 2}} = 10^{12} (\text{keV}/m_{\nu_\tau})^2 \text{ s.}$, but

the derelativization of primordial $\nu_{\mu 1}$ takes place at $t_{\nu_{\mu 1}} = 10^8 (\text{keV}/m_{\nu_{\tau}})^2 \text{s}$. Finally, we have the following parameters for $T_{\nu_{\mu 2}}$ in Eq. (29):

$$\begin{aligned} R_{f\nu_{\mu 2}} &= 22(1 \text{ keV}/m_{\nu_{\tau}})^3 \text{ Mpc.} \\ \Omega_{\nu_{\mu 2}} h^2 &= 1.03 \cdot 10^{-2} (m_{\nu_{\tau}}/\text{keV}) \end{aligned} \quad (38)$$

As we see, the hierarchy (1) induces a similar hierarchy of scales in the hierarchic decay scenario.

Let us note that the main HDS parameters (the mass of the unstable ν_{τ}) is severely constrained by the condition of the sufficient growth of small initial perturbations. Based on this condition, the data on the anisotropy of the thermal microwave background exclude $m_{\nu_{\tau}} > 2 \text{ keV}$.

Semiquantitative analysis of the obtained spectrum of density fluctuations, together with the estimations of typical scales of the large scale structure and superlarge scale structure arising in HDS, makes it possible to conclude that the cosmological structure, expected in the scenario under consideration, should be close to the observed one.

Note that if the problem of archioles is avoided, the second "standard" CDM solution appears, corresponding to an axionic CDM model with $F \sim 10^{10} \text{ GeV}$. The role of archioles deserves a special analysis in this scenario.

Inflation

The recent indications of the existence of microwave thermal background anisotropy, claimed in the COBE experiment [40], also seem to favor such a mixed scenario. Moreover, an analysis of the data obtained in Relict 1 experimental searches for large scale anisotropy of relic radiation, seems to favor unstable dark matter models of large scale structure formation. All the existing data and their analysis [41] also seem to favor "flat" Harrison-Zeldovich spectrum, predicted by simple one-field inflationary models (the chaotic inflationary scenario, in particular). Such a scenario can find its grounds in the framework of the presented model, since the singlet Higgs field η , determining the flavor independent mass term $\mu = G_{\eta} \langle \eta \rangle$, may self-consistently play the role of inflaton at $\langle \eta \rangle \sim m_{pl}$ and $G_{\eta} < v_{PQ}/m_{pl}$. The predicted spectrum of density fluctuations practically coincides with the "flat" one at $v_{PQ} < 10^{10} \text{ GeV}$.

Baryogenesis

Even at the presented level of "horizontal" $SU(2) * U(1) * SU(3)_H$ gauge unification, the model provides a mechanism for baryogenesis without GUT-induced baryon nonconservation. The mechanism combines the $(B + L)$ nonperturbative electroweak nonconservation at high temperatures with $\Delta L = 2$ nonequilibrium transitions, induced by Majorana neutrino interactions. Estimations [41] show, that the mechanism can

in principle reproduce the observed baryon asymmetry of the Universe for the allowed parameters of the model. So the proposed model provides a unified fundamental basis for a theoretical description of both the structure of elementary particles and the structure of the Universe. Such a unified approach to cosmological and particle phenomena is the brightest feature of the new science, CosmoParticle Physics, formed in the recent years in the confrontation of particle theory and cosmology. Unifying the separate results of studies of partial problems of cosmology and particle physics, the proposed model seems to be the first step on the way towards a realistic unified description of the unique fundamental grounds of the micro- and macro-world structure on the basis of flavor dynamics.

These ways to the highlights of the theory, based on the detailed elaboration of its "low energy" basis, may give valuable recommendations for the choice of realistic variant of a complete unified "theory of everything" (superstring theory, for example), that seems to be of evident importance in view of the existing theoretical uncertainties in the searches for fundamental grounds of physics and cosmology.

An important epistemological aspect of the presented studies is to be pointed out. We have demonstrated by this example the principal possibility of a detailed study of the multiparameter "hidden" sector of particle theory. The example of QFD with low-energy scale of family symmetry breaking provides a hope that a multiparameter model of superhigh energy physics, being elaborated in details, will lead to an amount of indirect effects accessible to experimental and observational tests, exceeding the number of independent parameters of the theory, so that an overdetermined set of equations with respect to these parameters might be deduced from the set of tests of the model predictions. So the general approach to experimental tests of a theory, based on overdetermined sets of equations for unknown theoretical parameters, can be realized in the framework of cosmoparticle physics. An analysis of a combination of effects predicted by the theory, provides its detailed study in cases when a direct experimental test is impossible.

Even this brief sketch of possible links between CosmoParticle Physics and space-time theory exhibits evident and mutual importance of their further interaction.

Acknowledgement

The work is performed in the framework of the project "CosmoParticle Physics" and partially supported by International Science Foundation grant MB9300 and Russian Foundation for Fundamental Research grants 93-02-02951, 93-02-03636.

References

- [1] J.K. Chkareuli, Pis'ma ZhETF 32 (1980), 684.

- [2] Z.G. Berezhiani and J.K. Chkareuli, *Pis'ma ZhETF* 35 (1982), 494; *Yadernaya Fizika* 37 (1983), 1043.
- [3] Z.G. Berezhiani, *Phys. Lett.* 129B (1983), 99.
- [4] P. Candelas, G. Horowitz, A. Strominger and E. Witten, *Nucl. Phys.* B258 (1985), 46.
- [5] E. Witten, *Nucl. Phys.* B258 (1985), 75.
- [6] K.S. Narain, 1986 *Phys. Lett.* 169B (1986), 41; H. Kawai, D. Lewellen and S.H. Tye, *Phys. Rev. Lett.* 57 (1986), 1832.
- [7] S.L. Glashow, and S. Weinberg, 1977, *Phys. Rev.* D15 (1977), 1958.
- [8] M. Gell-Mann, P. Ramond, and R. Slansky, 1979 in: "Supergravity", eds. P. Van Nieuwenhuizen and D. Freedman, North Holland, 1979, p. 186.
- [9] M.I. Vysotski, 1985, *Uspekhi Fiz. Nauk* 147 (1985), 100; H.P. Nilles, *Phys. Rep.* 86 (1983), 200.
- [10] R.D. Peccei and H.R. Quinn, *Phys. Rev.* D16 (1977), 1791.
- [11] A.R. Zhitnicki, 1980, *Yadernaya Fizika* 31 (1980), 497; M. Dine, F. Fishler and M. Srednicki, *Phys. Lett.* 104B (1981), 199; M. Wise, H. Georgi, and S.L. Glashow, *Phys. Rev. Lett.* 47 (1981), 402.
- [12] F. Wilczek, *Phys. Rev. Lett.* 49 (1982), 1549.
- [13] A.A. Anselm and N.G. Uraltzev, *ZhETF* 84 (1983), 1961.
- [14] V. Chikashige, R.N. Mahapatra and R.D. Peccei, *Phys. Rev. Lett.* 45 (1980), 1926.
- [15] Z.G. Berezhiani and M.Yu. Khlopov, *Yadernaya Fizika* 51 (1990), 1157; 51 (1990), 1479; 52 (1990), 96; *Z. Phys. C* 49 (1991), 73; Z.G. Berezhiani, M.Yu. Khlopov and R.R. Khomeriki, *Yadernaya Fizika* 52 (1990), 104, 538.
- [16] Z.G. Berezhiani and J.L. Chkareuli, *Pis'ma ZhETF* 37 (1983), 285.
- [17] Z.G. Berezhiani, *Phys. Lett.* 150B (1985), 177.
- [18] A.A. Anselm and Z.G. Berezhiani, *Phys. Lett.* 162 (1985), 349.
- [19] A.A. Anselm, *Pis'ma ZhETF* 36 (1982), 46; A.A. Anselm and N.G. Uraltzev, *Phys. Lett.* 116B (1982), 161.
- [20] J.E. Kim, *Phys. Rep.* 150 (1987), 1; H.Y. Cheng, *Phys. Rep.* 158 (1988), 1.
- [21] M.Yu. Khlopov, A.S. Sakharov, A.A. Shkiyaev, and A.L. Sudarikov, *Proc. 1 Int. Conf. on CosmoParticle Physics "Cosmion-94"*, Eds. M.Yu. Khlopov, et al., 1995. To be published by Editions Frontieres.
- [22] J.E. Kim, 1979, *Phys. Rev. Lett.* 43 (1979), 103; M.A. Shifman, A.I. Vainshtein and V.I. Zakharov, 1980, *Nucl. Phys.* B166 (1980).
- [23] M.I. Vysotski, Ya.B. Zeldovich, M.Yu. Khlopov and V.M. Chechetkin, *Pis'ma ZhETF* 27 (1978), 533; D.S. Dicus, E.W. Kolb, V.L. Teplitz and R.V. Wagoner, *Phys. Rev.* D18 (1978), 1829; M. Fukugita and S. Watamura, *Phys. Rev. Lett.* 48 (1982), 1522.
- [24] J. Ellis and K.A. Olive, *Phys. Lett.* 193B, 525; G. Raffelt and D. Seckel, *Phys. Rev. Lett.* 60 (1988), 1793.
- [25] Z.G. Berezhiani, A.S. Sakharov and M.Yu. Khlopov, *Yadernaya Fizika* 55 (1982), 100; Preprint DFTUZ 91.29, 1991.
- [26] N. Enrico and R. Esteban, *Phys. Lett.* B245 (1990), 109.
- [27] Z.G. Berezhiani, A.S. Sakharov and M.Yu. Khlopov, *Yadernaya Fizika* 7, 1992; N. Enrico and R. Esteban, *Phys. Lett.* B245 (1990), 109.
- [28] M.S. Turner, *Phys. Rev. Lett.* 60 (1988), 1796.
- [29] A.S. Sakharov and M.Yu. Khlopov, *Yadernaya Fizika* 56 (1993), 220.
- [30] A.S. Sakharov and M.Yu. Khlopov, *Yadernaya Fizika* 57 (1994), 514.
- [31] T. Vachaspati and A. Vilenkin, *Phys. Rev.* D30 (1984), 2036.
- [32] L. Abbott and P. Sikivie, *Phys. Lett.* 120B (1983), 133; J. Preskill, M. Wise and F. Wilczek, *Phys. Lett.* 120B (1983), 127; M. Dine and W. Fishler, *Phys. Lett.* 120B (1983), 137; A.G. Doroshkevich, M.Yu. Khlopov and A.A. Klypin, *MNRAS* 211 (1989), 277.
- [33] M.S. Turner, G. Steigman and L.M. Krauss, *Phys. Rev. Lett.* 146b, 2090; G. Gelmini, D. Schramm and J.W.F. Valle, *Phys. Lett.* 146B (1984), 311; A.G. Doroshkevich, A.A. Klypin and M.Yu. Khlopov, *Pis'ma Astron. Zh.* 11 (1985), 483; *Astron. Zh.* 65 (1988), 248; in: "Large Scale Structures of the Universe", eds. A. Szalay and J. Audouze, D. Reidel, 1988, p. 293.
- [34] J. Ipser and D. Sikivie, *Phys. Rev. Lett.* 50 (1983), 925.
- [35] A.S. Sakharov and M.Yu. Khlopov, *Yadernaya Fizika* 57 (1994), 690.
- [36] J. Madsen, in: "Particle Astrophysics. The Early Universe and Cosmic Structures", ed. J.M. Alimi, A. Blanchard, A. Bouquet, F. Martin de Volnay, J. Tran Thanh Van. Editions Frontieres, 1990, p. 205.
- [37] S. Tremaine, J.E. Gunn, *Phys. Rev. Lett.* 42 (1979), 407.
- [38] J.M. Bardeen, J.R. Bond, N. Kaiser and A. Szalay, *Ap. J.* 304 (1986), 15 (BBKS).
- [39] M. Davis, M. Lecar, T. Pryor and E. Witten, *Ap. J.* 250 (1981), 424.
- [40] G.F. Smoot et al, 1992, *Astrophys. J.* 300, L90; E.L. Wright et al, *Astrophys. J.* 300 (1992), L100.
- [41] M.A. Luty, *Phys. Rev.* D45 (1992), 455.